Security Classification

DOCUMENT CONTROL DATA - R & D

Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

AD 744656

1. ORIGINATING ACTIVITY (Corporate author) AERO-ELECTRONIC TECHNOLOGY DEPARTMENT NAVAL AIR DEVELOPMENT CENTER WARMINSTER, PENNSYLVANIA 18974	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP

3. REPORT TITLE

EYE-SAFE OPERATION OF ILLUMINATOR-AIDED IMAGING SYSTEMS

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

PHASE REPORT

5. AUTHOR(S) (First name, middle initial, last name)

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6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
19 MAY 1972	17	3

8a. CONTRACT OR GRANT NO. b. PROJECT NO. NAVSHIPSYSCOM PROJECT ORDER PO 2-0026 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) NADC-72041-AE 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY NAVAL AIR SYSTEMS COMMAND DEPARTMENT OF THE NAVY

13. ABSTRACT

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DD FORM 1 NOV 65 1473 (PAGE 1)

UNCLASSIFIED

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
EYE-SAFETY LASER SAFETY						

DEPARTMENT OF THE NAVY
NAVAL AIR DEVELOPMENT CENTER
WARMINSTER, PA. 18974

Aero-Electronic Technology Department

REPORT NO. NADC-72041-AE 19 May 1972

EYE-SAFE OPERATION OF ILLUMINATOR-AIDED IMAGING SYSTEMS

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Eye-safe levels recommended by the three services are given in terms of maximum permissible corneal irradiance. The effect of laser sources with large exit pupils on the eye-safety calculations is discussed. Formulas for determining safe operating conditions are given. Six examples of eye-safety computations are given using the figures provided.

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S U M M A R Y

INTRODUCTION

The performance of low-light level imaging devices can be greatly enhanced when used with pulsed laser "illuminators." However, precautions must be taken to insure that the maximum irradiance level which can impinge on the eye of a viewer at a specified range within the output beam of the laser does not exceed a specified safe level. The most popular type of laser for this application is the laser diode array. GaAs (Gallium Arsenide) laser diode arrays, radiating in a narrow spectral band at about 0.86 micron, have achieved peak power levels of 2 kw. Pulse width and repetition rate can be varied over a wide range, and duty cycles as high as 2 percent are readily achieved. The output power of a laser diode array is smoothed, converged, and projected with various optical components to form a homogenous beam with a divergence typically ranging from 1-to-10 degrees.

The human eye, when viewing the laser from a point within the output beam of the laser, will form an image of the laser optic's exit pupil on the retina. Given an unfavorable combination of such conditions as range, laser power, beam divergence, exit aperture, and atmospheric attenuation, the laser can produce irradiance levels at the retina sufficient to cause irreparable damage. The considerations that must be made to avoid this condition are discussed herein.

RESULTS AND CONCLUSIONS

1. The Army-Navy eye-safety standard for laser operation necessitates considerable care in the use of laser diode array illuminators. The standard recommended by the Air Force does not restrict the use of most GaAs laser illuminators currently available.

2. The assumption that a laser is a point source is overly restrictive in the case of many laser diode array illuminators. Treating such lasers as extended sources greatly alleviates the problem of eye-safety precautions with GaAs laser illuminators.

3. Given the laser exit aperture and beam divergence, the laser radiance can be limited to a safe level by limiting output power.

4. Given the laser output power and beam divergence, the laser radiance can be limited to a safe level if a sufficiently large exit aperture is used.

RECOMMENDATIONS

1. It is recommended that existing disparities between DOD agencies concerning maximum permissible exposure levels be resolved, and that a unified eye-safety standard be established.

2. It is recommended that laser eye-safety standards be written to explicitly include provisions for large aperture lasers.

3. It is recommended that future design of optics for laser diode arrays take into consideration the problem of eye-safety, so that, wherever possible, exit diameters are large enough to limit laser radiance to safe levels.

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EXISTING GUIDELINES

There is no general agreement on the maximum permissible exposure level. In table I, the maximum corneal irradiance levels recommended by various agencies are listed. These levels are based on the assumption that the entrance pupil of the eye is at its maximum (about 7 millimeters), that the laser exit pupil subtends an angle at the eye too small to be resolved (less than 1 milliradian), and that the laser wavelength is between 0.4 and 1.4 microns.

TABLE I

RECOMMENDED MAXIMUM PERMISSIBLE POWER DENSITY LEVELS AT CORNEA

Recommending Agency	Maximum Corneal Irradiance ($watts/cm^2$)
Army (ref (a))	1×10^{-6}
Navy (ref (a))	1×10^{-6}
Air Force (ref (b))	2600×10^{-6}

EFFECT OF FINITE SOURCE AREA

The maximum corneal irradiance levels given above are based on the assumption that the laser will not be resolvable to the human eye. In this instance, referred to herein as the point source case, the retinal irradiance will vary inversely as the square of the distance from the eye to the source. However, this assumption may be overly restrictive in the case of laser diode array sources. The exit aperture of GaAs lasers currently in use is often large enough to be resolvable at a distance far enough so that the maximum corneal irradiance level is not exceeded. At closer distances, while the corneal irradiance level increases above the safe level, the retinal image of the laser output is increasing in area by the same proportion, and the retinal irradiance remains constant at a safe level. In this condition, the extended source case, the laser is eye safe at all practical distances. At extremely close distances, inhomegenieties in the laser radiance may become resolvable, thereby producing retinal "hot spots." In reference (c), eye safety calculations are made for a GaAs laser array used with the NVASS (Night Vision Airborne Surveillance System). In this analysis, the "effective corneal irradiance," was computed taking into consideration

the extended size of the exit aperture. These computations show that the retinal irradiance could not exceed the most restrictive maximum levels advocated by the Army and the Navy at any distance; whereas, if this laser had been assumed to be a point source, this level would have been exceeded at a range of approximately 200 meters.

DETERMINATION OF EYE-SAFE CONDITIONS

As was shown, the laser exit pupil size should be considered in eye-safety calculations. In figure 1, the minimum resolvable element diameter is plotted as a function of range. This relationship is based on the assumptions used in reference (c): that the smallest possible retinal spot diameter is 10 microns; and that the eye's focal length is 17 millimeters. If, at a given range, the laser exit pupil exceeds the minimum element diameter given in figure 1, it should be considered an extended source at that range, otherwise it can be taken as a point source.

If the laser is effectively a point source, the maximum permissible corneal irradiance level should not be exceeded. The corneal irradiance level can be computed as follows:

$$H_c \cong \frac{P}{\theta_r \, \theta_h \, R^2} \, e^{-\alpha R}, \text{ where}$$

H_c is the corneal irradiance (watts/m^2),

P is the total laser average power (watts),

R is the viewing range (meters),

θ_v is the laser divergence angle in the vertical direction (radians),

θ_h is the laser divergence angle in the horizontal direction (radians), and

α is a constant relating the atmospheric attenuation (meters^{-1}).

This expression is a close approximation where θ_v and θ_h are less than about 0.2 radian. In figure 2 the maximum permissible power is plotted as a function of range, assuming no atmospheric loss ($\alpha = 0$), and a maximum permissible corneal irradiance of 1×10^{-6} watts/cm^2 for several likely combinations of θ_v and θ_h. This is the most restrictive of the maximum exposure levels given in table I. If the Air Force standard is to be applied, the power level can be multiplied by 2600.

If, at the prescribed range, the laser exit pupil is larger than the minimum given in figure 1, the laser can be assumed to be an extended source, and the "effective corneal irradiance" can be computed as in the appendix to reference (c).

$$H_c \text{ (effective)} \cong \frac{P}{\theta_v \, \theta_h} \; \frac{d_m^{\,2}}{f^2 \; d^2} \; e^{-\alpha R},$$

where d_m is the minimum retinal spot diameter, f is the eye's focal length and d is the laser diameter. In figure 3, the maximum laser power is plotted as a function of laser exit pupil diameter again assuming no atmospheric attenuation. This relationship assumes a maximum effective corneal irradiance level of 1×10^{-6} watts/cm^2. Again, this value can be adjusted by the appropriate factors for the more liberal standards of the Air Force.

The power levels given in figures 2 and 3 can also be adjusted downward to provide the safety factors recommended by the Army and Navy.

D I S C U S S I O N

As is evidenced by table I, considerable disparity exists between the various agencies as to what constitutes a safe exposure level. Few, if any GaAs lasers in use today are capable of exceeding the Air Force guideline.

On the other hand, the present Army-Navy standard necessitates considerable care in the use of GaAs lasers. Until general agreement is reached, laser operations at NAVAIRDEVCEN will be subject to the more conservative controls of the Army-Navy standard.

S A M P L E   C O M P U T A T I O N S

The following are sample cases to illustrate the use of figures 1, 2, and 3.

Symbols

P = laser power (watts)

R = viewing range (yards)

d = laser exit pupil diameter (feet)

θ_v = vertical beam divergence (degrees)

θ_h = horizontal beam divergence (degrees)

S = safety factor (2 for field operation, 10 for laboratory use)

Case I:

Given:

R = 100 yards

$\theta_v = \theta_h = 3°$

d = 0.3 feet

S = 2 (field operation)

Find Pm, the maximum permissible laser power.

Since the minimum resolvable diameter at 100 yards is given in figure 1 as 0.175 feet, the 0.3 foot diameter laser should be considered as an extended source Applying figure 3, using the 3° x 3° line, the maximum power that should be used with a 0.3 foot exit aperture is 0.65 watts. Applying a safety factor of 2, the laser power should not exceed 0.32 watts.

$P \leq 0.32$ watts

Case II:

Given:

R = 100 yards

$\theta_v = \theta_h = 1.7°$

d = 0.1 foot

S = 2 (field operation)

Find Pm, the maximum permissible laser power level.

At 100 yards, figure 1 shows that this laser should be considered as a point source. Therefore, figure 2 should be used. At 100 yards with a 1.7° x 1.7° laser, the power level should not exceed 0.08 watts. Applying the safety factor

$P \leq 0.04$ watts

Case III:

Given:

$P = 5$ watts

$\theta_V = \theta_h = 3°$

$d = 0.3$ feet

$S = 2$

Find Rm, the minimum permissible viewing range.

Applying the safety factor, a value of 10 watts is used in figure 2 to determine the eye-safe distance of 660 yards. At 660 yards, figure 1 shows that the eye can resolve objects larger than 1.2 feet, thus this laser must be considered a point source, and the maximum range is as stated:

$R \geq 660$ yards

Case IV:

Given:

$P = 0.20$ watts

$\theta_V = \theta_h = 3°$

$d = 0.3$ feet

$S = 2$

Find Rm, the minimum permissible viewing distance.

Figure 2 shows that a point source emitting 0.4 watts (PxS) into a 3° x 3° beam could be safely viewed at 130 yards. However, figure 1 shows that a 0.3-foot diameter could be resolved at 130 yards. Thus if the viewing range is decreased below this point, the retinal irradiance remains unchanged, and theoretically the laser could be viewed at any range. However, at extremely close ranges, depending on the exact nature of the optics, the effective exit pupil may diminish, or inhomogenieties in the radiance may become resolvable. Therefore, the characteristics of the laser at ranges less than 130 yards should be known before the eye-safe range is lowered. In many cases, however, the safe viewing range can be significantly reduced below the distance derived from figure 2.

Case V:

Given:

$P = 1.0$ watts

θ_v, $\theta_h = 2.50$

$S = 2$ (field of operation)

Find dm, the minimum effective laser exit diameter for safe viewing at any range.

Using $P = 2.0$ watts, figure 2 indicates a safe point source viewing distance of 360 yards. At this distance, figure 1 shows that a diameter of 0.63 foot could be resolved. Thus if the laser exit pupil were made at least this large, it could be viewed at any distance, assuming the effective exit aperture does not decrease with distance.

$d \geq 0.63$ feet.

Case VI:

Given:

$P = 0.3$ watts

$R = 500$ yards

$d = 0.3$ feet

$S = 10$ (lab operation)

Find $\theta_{v_m} = \theta_{h_m}$, the minimum beam divergence for safe viewing at 500 yards.

Using a power level of 3.0 watts, figure 2 shows that a laser with $\theta_v = \theta_h = 1.7°$ is unsafe, while a divergence of $2.5° \times 2.5°$ will result in eye safe operation at 500 yards. Interpolation indicates a safe divergence:

$\theta_v = \theta_h = 2°$

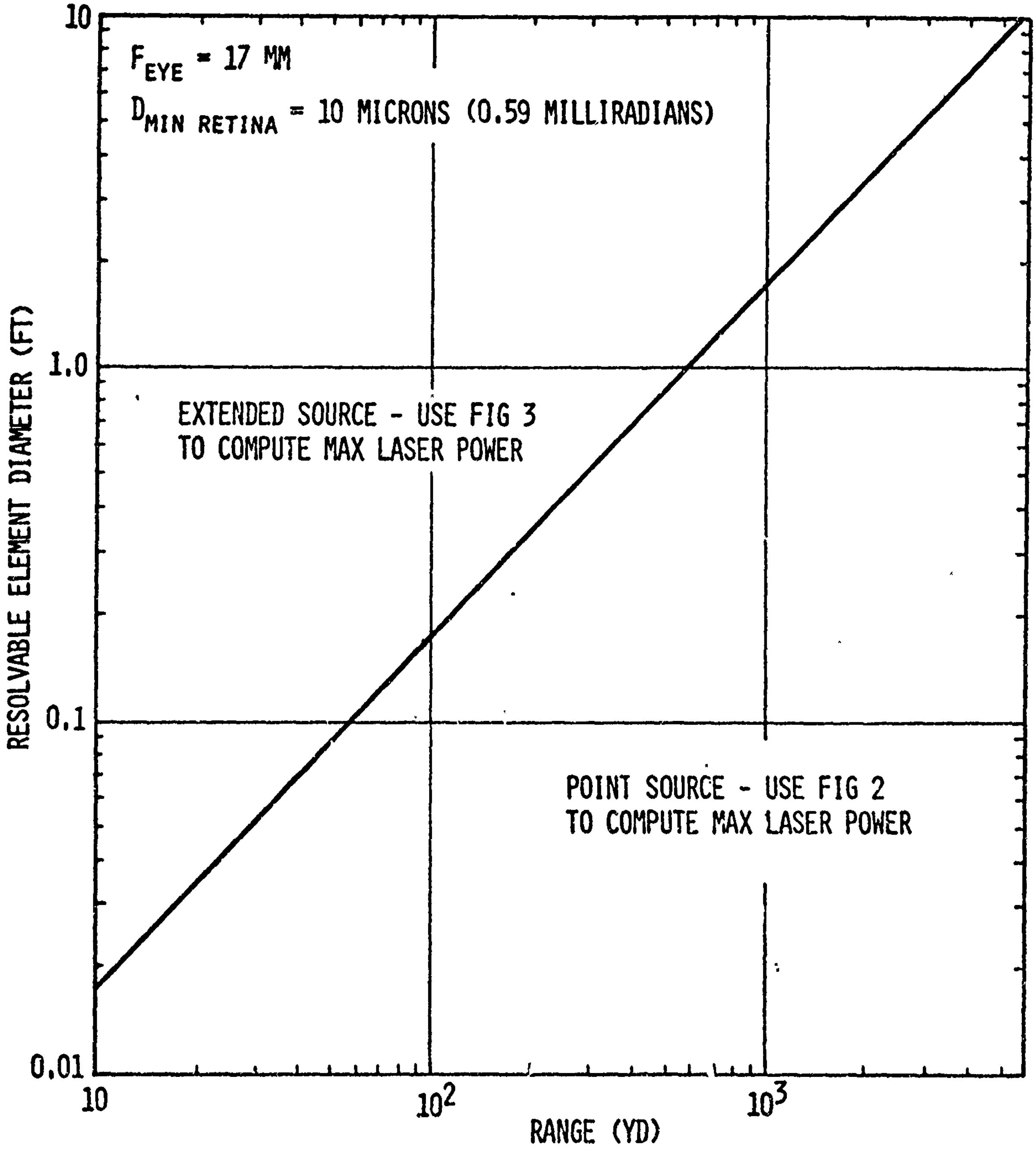

FIGURE 1 - Minimum Resolvable Diameter Versus Range

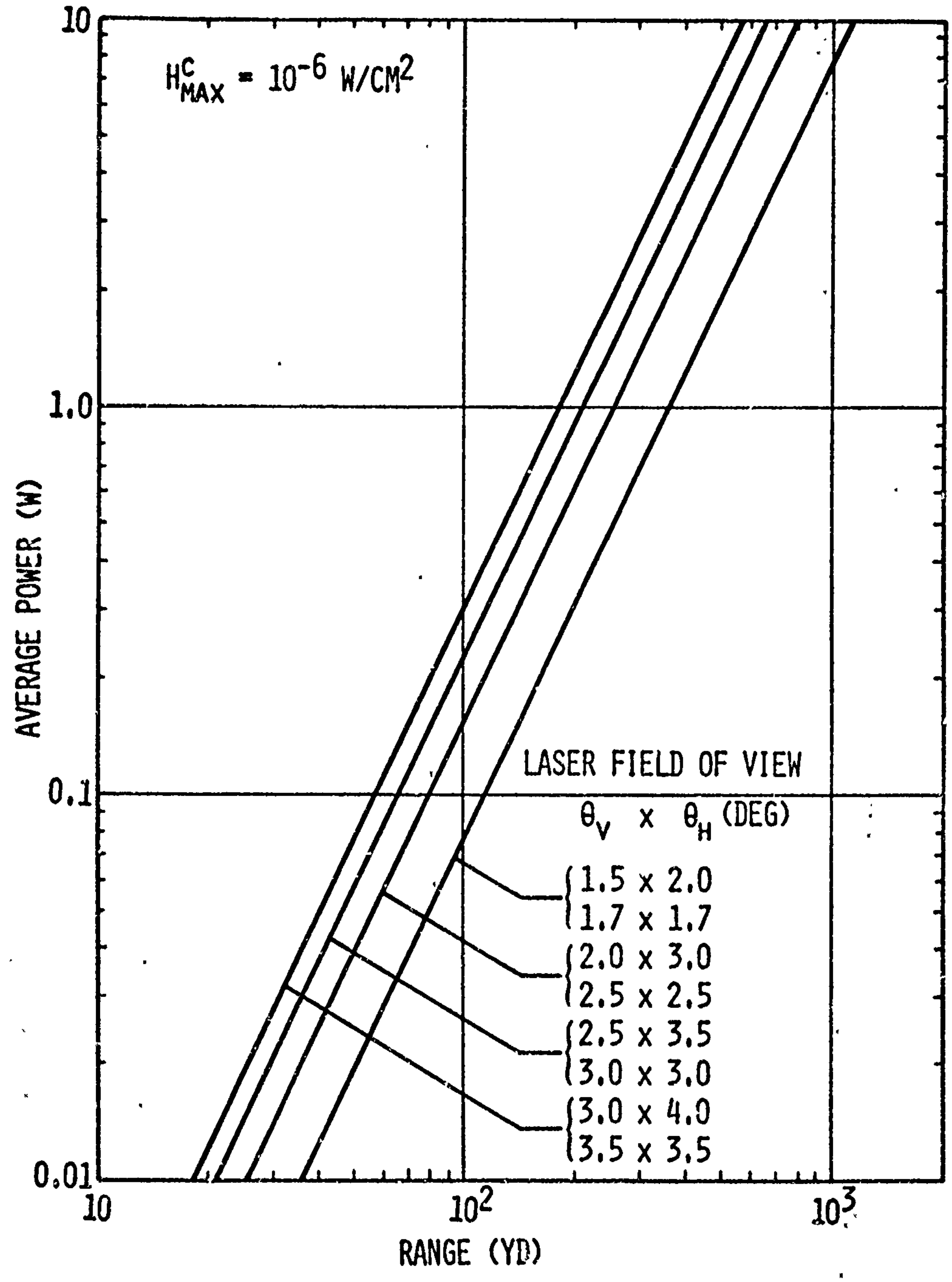

FIGURE 2 - Maximum Laser Power Levels Versus Range

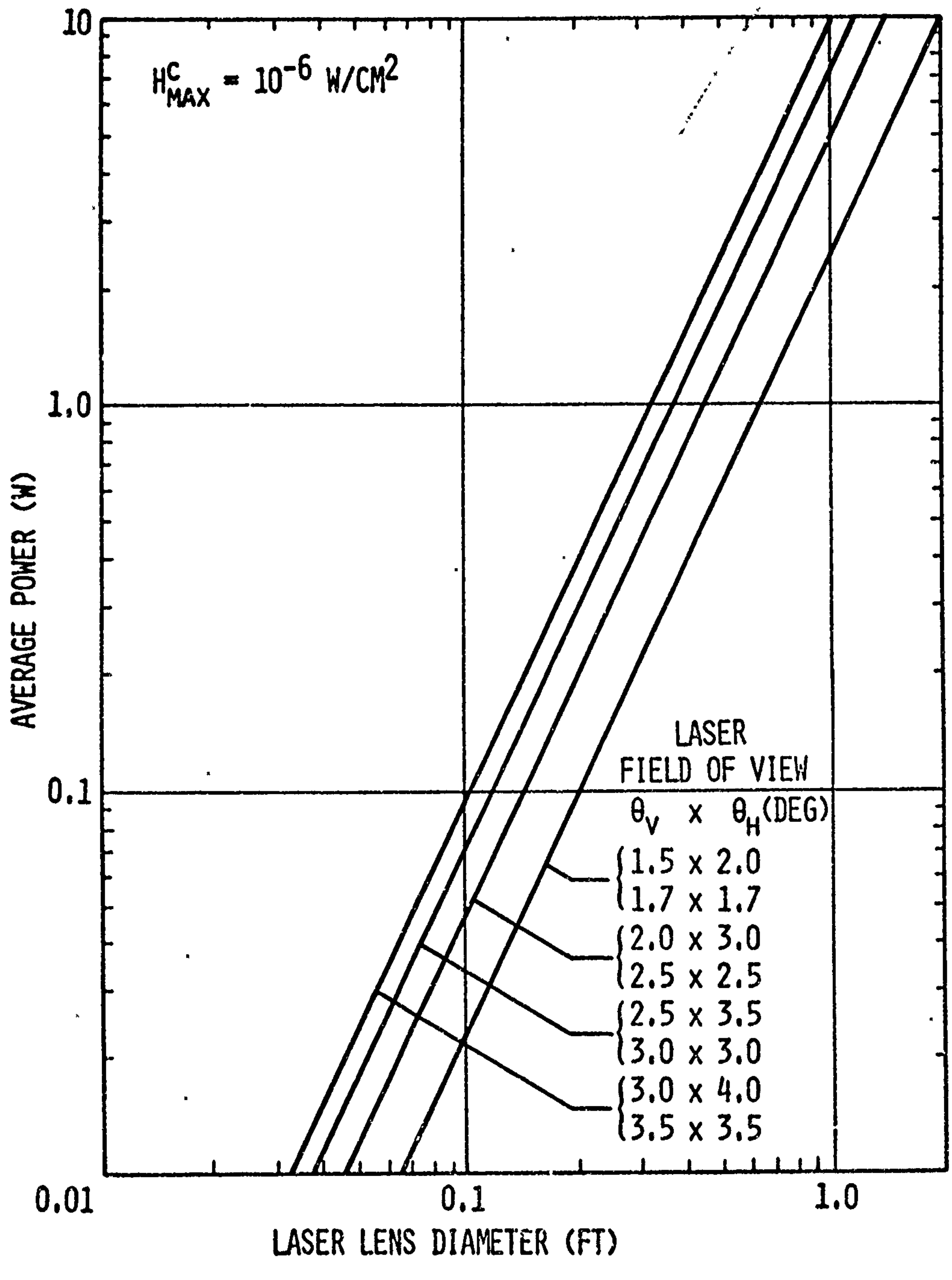

FIGURE 3 - Maximum Laser Power Versus Laser Diameter